Tunable, high-repetition-rate, harmonically mode-locked ytterbium fiber laser

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We report a ytterbium fiber laser mode locked at its 281st harmonic, which corresponds to a repetition rate greater than 10 GHz. The laser produces linearly polarized, 2-ps pulses with up to 38-mW of average output power. The mode-locked pulses are tunable over a 58-nm window centered on 1053 nm. © 2004 Optical Society of America

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Fiber laser and amplifier development in the wavelength region near 1 μm has experienced significant progress owing to the exceptional efficiency and gain bandwidth of ytterbium-doped fibers.[1–5] In fact, both ytterbium fiber lasers and amplifiers are becoming more attractive than their bulk counterparts because of their confined spatial mode, impressive bandwidth, good pump absorption, ease of alignment, and inherent compatibility with optical fiber. To date, however, experimental efforts regarding ytterbium fiber lasers have been directed only toward fundamental mode locking, which typically limits pulse repetition rates to below 100 MHz.[1–4]

This Letter focuses on another important parameter of mode-locked lasers that has thus far attracted little attention in this wavelength regime—high repetition rate. High-repetition-rate ytterbium fiber lasers would be a useful source of the ultrafast picket-fence pulse trains that have been proposed to improve the performance of fusion laser systems.[6] In this scheme, shaped nanosecond pulses are replaced by a train of ultrafast picket pulses that deliver the same average power while increasing the third-harmonic conversion efficiency. A high-repetition-rate and broadly tunable source would also be useful for synchronously pumping multigigahertz optical parametric oscillators.[7]

The laser considered in this research uses a 976-nm-pumped linear cavity, shown in Fig. 1, similar to that reported by Lefort *et al.* in 2002.[2] A bulk phase modulator[8] actively FM mode locks the laser, allowing synchronization to an external reference frequency. Velocity matching between the optical and microwave fields in the modulator's $LiNbO_3$ crystal, in conjunction with a resonant design, offers efficient phase modulation at the device's resonance frequency ($\approx$10.3 GHz). A synthesized microwave-signal generator (HP Model 83732B) amplified by a traveling-wave tube amplifier (Hughes Model 8010H) provides up to 10 W of microwave power to the modulator, which was measured to have a single-pass modulation depth of $\approx$0.45 rad. To reduce intracavity loss, the crystal facets were antireflection coated, resulting in an insertion loss of <1% at 1053 nm.

The laser delivers output to three different ports, as shown in Fig. 1. The combination of a half-wave plate ($\lambda/2$) and a polarizing beam splitter not only provides variable output coupling, yielding up to 38 mW from port 1 and up to 6.5 mW from port 2, but also selects the optimum polarization for the FM modulator and the grating pair. Depolarization in the fiber section of the cavity results in 2.5 mW of leakage from port 3.

The mode-locking threshold was measured to be as low as 30 mW, but the pump laser was operated at a power of 150 mW in an effort to maximize the output power and facilitate autocorrelation measurements. All the results presented in this Letter were obtained with this pump power and the output from port 1, where the laser has a slope efficiency of 32% (if all three ports are considered, the slope efficiency is 40%). The cavity also incorporates a grating pair, which compensates the normal dispersion introduced by 1 m of ytterbium-doped fiber and 1.2 m of fiber associated with the 976/1050 wavelength-division multiplexing coupler. The overall second- and third-order cavity dispersions were measured to be -6.3×10^4 fs^2 and 30.6×10^4 fs^3, respectively, revealing that this laser is within the soliton regime.

A typical mode-locked pulse spectrum, measured with an optical spectrum analyzer (Ando Model AQ6315A), reveals a bandwidth of 0.8 nm as seen in Fig. 2. This spectrum is best fit by a sech^2 function, shown by the dashed curve. The dotted curve shows a Gaussian fit for comparison. If the pulse spectrum is a sech, a 0.8-nm bandwidth (FWHM) implies a 1.5-ps (FWHM) transform-limited sech pulse. According to simple FM mode-locking theory, a FM modulator in a purely linear dispersionless cavity should produce chirped Gaussian output pulses with Gaussian spectra.[9] In light of this, our spectral measurements suggest that cavity dispersion, fiber nonlinearity, and modulator-induced chirp play a significant role in shaping the laser pulses.[10]

An interferometric autocorrelator employing two-photon absorption (TPA) in the photocathode of a photomultiplier tube was used to perform autocorrelation measurements[11] (Fig. 3). This sensitive diagnostic

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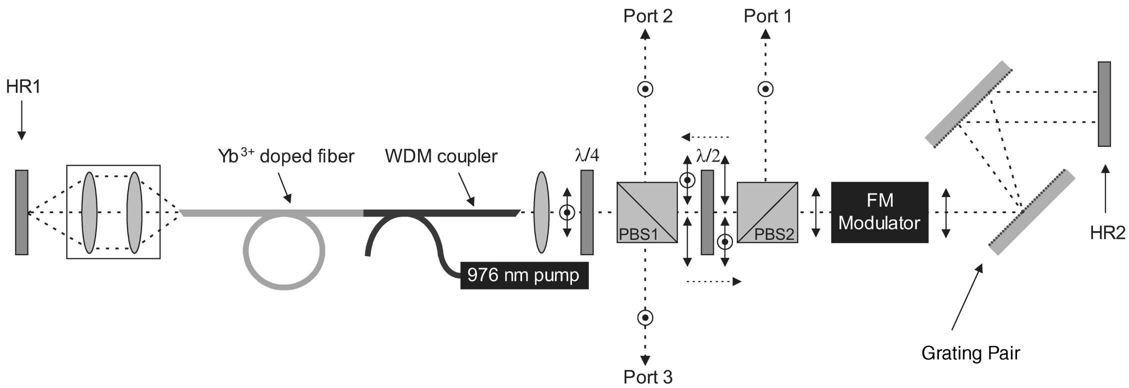

Fig. 1. Laser cavity configuration: HR1, HR2, high-reflectivity mirrors; PBS1, PBS2, polarizing beam splitters; WDM, 976/1050-nm wavelength-division multiplexer. The double-sided arrows and the dots surrounded by circles represent the horizontal and vertical polarizations, respectively.

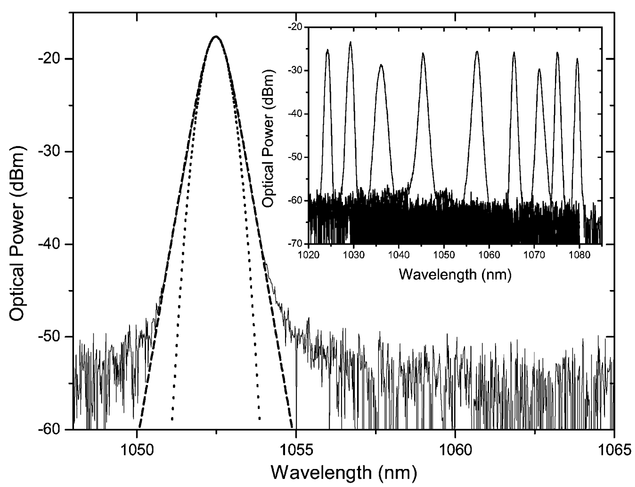

Fig. 2. Mode-locked optical pulse spectrum and its associated $sech^2$ fit (shown by the dashed curve). The dotted curve shows the corresponding Gaussian fit for comparison. Inset, superimposed mode-locked spectra illustrating the 1022–1080-nm tuning range.

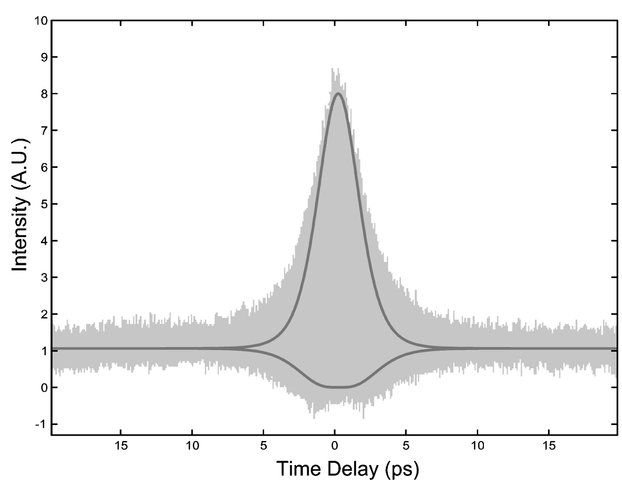

Fig. 3. Autocorrelation results. The fit was obtained by use of the TPA response to a 2-ps sech pulse.

was required to measure the pulses, whose low energy ($\lesssim 4$ pJ) resulted from the large number of pulses simultaneously circulating in the laser cavity. The autocorrelation trace was best fit[12] by the TPA response to a sech pulse, indicating a pulse width of 2.0 ± 0.2 ps (FWHM) and revealing that this laser's time–bandwidth product is 0.43 ± 0.04. As a consequence of the low pulse power, not only was it difficult to obtain autocorrelation traces, but also they had signal-to-noise ratios of ≈ 5.

Mode-locked operation was achieved with central wavelengths ranging from 1022 to 1080 nm by inserting a knife edge (not depicted in Fig. 1) in front of a high-reflectivity mirror (HR2) and adjusting its position. The central wavelength also depended on the driving modulation frequency, the cavity length, and the angular position of HR2. The effect of tuning on the pulse spectrum is shown in the inset in Fig. 2, where several different spectra in the tuning range 1022–1080 nm have been superimposed on one another. The spectral shape varies little over the tuning range, although the spectra centered on 1030 nm have the largest bandwidth.

Side-mode suppression and timing jitter are two common figures of merit used to evaluate the quality of a mode-locked pulse train. These quantities were derived from the pulse-train power spectrum shown in Fig. 4 and were obtained with a 25-GHz photodetector with a nominally flat frequency response (New Focus Model 1414) and a 26.5-GHz microwave spectrum analyzer (Agilent Model E4407B). As expected, the microwave spectrum shown in the inset in Fig. 4 is composed of peaks at the 10.31455-GHz driving frequency, its harmonics, and much weaker structures spaced by the 36.65-MHz fundamental repetition rate of the laser cavity (not visible in the inset), which are caused by supermode noise.[13] A side-mode suppression of greater than 72 dB was measured with respect to the largest of these side modes, as shown in the main figure. Dividing the laser's mode-locked repetition rate by its fundamental repetition rate reveals that there are 281 pulses simultaneously circulating in this cavity.

Since the inset in Fig. 4 shows that each peak is δ-function-like, having a FWHM narrower than the minimum resolution (1 Hz) of the spectrum analyzer, the timing jitter and pulse energy fluctuations of the output pulse train were characterized. An upper

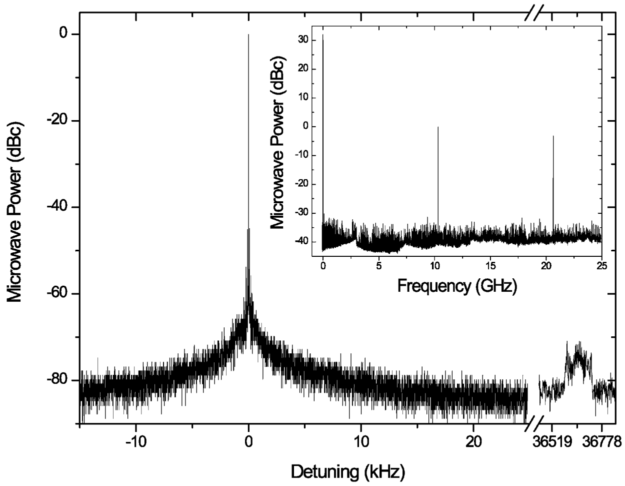

Fig. 4. Microwave spectrum of the laser versus detuning from the 10.31455-GHz modulation frequency. The horizontal axis is broken to show the closest supermode noise peak, which is detuned from the carrier by the fundamental repetition rate of the laser. Inset, dc contribution, ≈10.3-GHz mode-locked repetition rate, and the repetition rate's first harmonic located at ≈20.6 GHz. Note that the strength of the noise floor has increased in the inset as a result of the reduced resolution required to display such a broad frequency range.

bound on the rms timing jitter is related to the integrated spectral power over the offset frequency range $f_l - f_h$ according to[14]

$$\sigma = \frac{1}{2\pi f_m}\left[2\int_{f_l}^{f_h} L(f)\mathrm{d}f\right]^{1/2}, \tag{1}$$

where σ is the rms timing jitter, f_m is the repetition frequency of the mth harmonic around which this measurement is made, and $L(f)$ is the single-sided phase-noise spectral density detuned from f_m. Integration of the ≈20.6-GHz peak over an offset range from 10 Hz to 12 kHz yields an upper bound on rms timing jitter of 370 fs, which is only slightly larger than the 283-fs jitter measured for the microwave-signal generator with the same range. Above 12 kHz the noise floor of the spectrum analyzer dominated $L(f)$, which prohibited an accurate jitter quantization over the typically quoted range (10 Hz to 10 MHz). The rms energy fluctuations were not limited by the spectrum analyzer and were quantified[14] over the 10-Hz-to-10-MHz range, indicating a rms fluctuation of 16.9 fJ, which corresponds to an energy fluctuation of 0.85% for the 2-pJ pulses.

In conclusion, a tunable, high-repetition-rate, mode-locked, ytterbium fiber laser has been demonstrated. The sech^2 spectrum indicates that cavity dispersion, fiber nonlinearity, and modulator-induced chirp play a role in shaping the laser pulses. The pulse-train timing jitter was found to be primarily due to the electronics and could be reduced by use of a cleaner signal generator for jitter-sensitive applications. Finally, this laser's output pulse train consisting of linearly polarized, 2-ps pulses could produce up to 38 mW of average power, making it suitable for many future applications.

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